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An Artificial Transmission Line Experiment to Show Signal Processing Methods

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Abstract

The traditional artificial transmission line can provide needed experience in interpreting data. Particularly, in laboratories, the high cost of microwave sources, slotted lines, and instrumentation calls for an economical demonstration of the principles of wave propagation. The traditional Leecher Line experiments are troubled with high voltage signal sources (safety aspects) needed for neon bulb displays that do not unnecessarily load the signal source. Further, numerical values are not easily obtained from that light-on, light-off technology. The experiment described can illustrate reflected waves, matching lines, and spectral estimates using Bayesian methods. If desired, time domain testing can be illustrated with pulse sources.

Keywords- Transmission Lines, Microwaves, SWR, Bayesian methods

1. Introduction

In a microwave or transmission line course, the costs of apparatus are very high. Established laboratories, with a legacy of instrumentation, can readily utilize available equipment. Other schools, faced with high costs, space limitations, and priorities of research, need an economical answer to hands-on examination of fundamental principles. The artificial transmission line is capable of producing many of those benefits at costs that all schools can afford. Furthermore, the software which is currently available to the undergraduate can provide interpretation not readily obtained in the prior decade..

2. Apparatus

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In many schools, the artificial transmission line has been a standard experiment. [1] It is readily fabricated from low cost components. The one illustrated [Figure 1] cost less than 30 Yuan (RMB), an equivalent of less than $4.00 U.S. Surely, this is a reasonable cost for any laboratory.

The transmission line consists of repeated sections of L, C, as shown Figure 2.

The expressions for characteristic impedance, propagation constant, and group velocity can be found in most elementary electromagnetics books. A good web site for the telegrapher's equations is [2].

The related parameters are [3]:

$$Z_0 = \sqrt{\frac{L}{C}} \text{ (Characteristic Impedance)} \quad (1)$$

$$\beta = 2\pi f \sqrt{LC} \text{ (propagation constant)} \quad (2)$$

$$\text{Group Velocity} = \frac{1}{\sqrt{LC}} \quad (3)$$

Our choice was a characteristic impedance of 50 Ω as most laboratory generators are in this range. The tolerances on the components resulted in our achieved characteristic impedance of 55 Ω, a 10% error. Wanting small physical size, we chose 100 μH inductors. These inductors have a sufficiently high Q factor at the frequencies we intended to work (kilohertz range). Larger inductor size will provide a higher Q factor without major size increase. Having chosen the inductor and the characteristic impedance, the capacitor value was fixed as:

$$C = \frac{L}{Z_0^{\ 2}} = 0.04\mu F \quad (4)$$

Keeping with the philosophy to use standard component sizes, we chose the closest 20% component, a 0.033 μF capacitor.

Economical signal sources are readily available in the kilohertz range. The lower range was arbitrarily set at 30 kHz. At this frequency, the propagation constant is

$$\beta = 2\pi f \sqrt{LC} = 0.34 rad / section$$

$$\text{(9.7 degrees/section)} \quad (5)$$

To illustrate the minimal equipment demand, the students read the voltage from the oscilloscope, measuring the voltage amplitude in screen divisions.

Figure.3 graph shows the measurement of voltage along the taps of the transmission line.

Terminating the line with a 50 Ω resistor resulted in a relatively flat graph of voltage versus tap position. The slight mismatch gives a small variation in voltage, as does the attenuation of the line. Since the graph is minimally useful , it is not shown.

3. Results

The delay per section is

$$\text{Delay per section} = \frac{1}{velocity} = \sqrt{LC} = 1.8\mu s / section \quad (6)$$

A pulse generator may be used to examine pulse delay, but the rounding of the pulse shape (due to dispersion of the line) makes this a less useful display.

To compute the length of the transmission line, the voltage at the input tap was measured. The variation of voltage with frequency at the input tap is due to successive reflected waves which cancel part of the input wave. The frequency was varied from the sinusoidal source over the range of 30 kHz to 90 kHz. The voltage observed at the input is shown in Figure 4.

Successive nulls (the pseudoperiod) in Figure 4 occur 360 degrees apart in phase shift.

$$(\beta_2 - \beta_1) \times z = 2\pi \tag{7}$$

Here, z is the transmission line length (in taps) and the β values are associated with successive nulls. We call the difference (in Hz) between successive nulls the pseudoperiod. The reciprocal of the pseudoperiod is the pseudofrequency.

$$Pseudoperiod = \frac{1}{\text{pseudofrequency}} = \frac{1}{6.0 \times 10^{-5} / Hz} = 1.7 \times 10^4\, Hz \tag{8}$$

This would predict a number of taps as:

$$z = \frac{2\pi}{2\pi \times pseudoperiod\sqrt{LC}} = \frac{1}{(1.7 \times 10^4)(1.82 \times 10^{-6})} = 33 taps \tag{9}$$

This is an error of 13 %. In all these measurements, the student uses the scale divisions of the oscilloscope as the voltmeter, a matter of economy. Low frequency oscilloscopes are adequate to display the signal.

In Figure 5, we see the effects of attenuation and the successive canceling of incident and reflected wave. By knowing the frequency difference between successive nulls, we have computed the time of signal (incident and reflected wave) to transit the length of 2 ℓ, where ℓ is the length (in meters, if inductance and capacitance values are per unit length values.

The limited number of peaks and nulls makes the question of the frequency difference between nulls problematical. This gives us the opportunity to point out that spectral estimation (in this case, a pseudospectrum, as the horizontal axis is already in frequency) can readily be achieved using Bayes' Theorem. An excellent tutorial on the method is available from G. Larry Bretthorst's [3] web site bretthorst@wusl.edu.

4. Analysis method

The result of the spectral estimation is shown in Figure 5. A program is available in Bretthorst's book at his web site. An estimation of both the decay rate and the delay time can be obtained from this signal processing. We chose a simple constant to describe the attenuation model, f.:

$$f(m, n, x_j) = e^{(-a(m)x(j))} \cos(2\pi b(n) x(j)) \tag{10}$$

We preferred to use x(j) as the independent variable, as we prefer to use f for the model (to be consistent with Bretthorst's notation).

One might surmise that the model has weaknesses. For example, the propagation constant varies, for a lossy line, with the square root of resistance per unit length. Further, the skin depth in metal varies inversely with the square root of signal frequency. Thus, the choice of a constant value of the attenuation parameter, even over a limited frequency range, is suspect. The choice of cosine for the oscillatory term is based on better knowledge, as we expect a maximum in the oscillatory pattern of Figure 5 to occur at zero frequency.

In Bretthorst's method, a model is chosen for theoretical reasons. This model is varied by changing parameters of the model. This model is compared to the actual data obtained in the experiment. Any prior information of the nature of the hypothesis is contained in the prior, P(H|I). This expression is:

$$P(H \mid D, I) = \frac{P(H \mid I) P(D \mid H, I)}{P(D \mid I)} \tag{11}$$

Since the term P(D|I) does not contain the hypothesis, it serves as a scale factor, only. The term, P(D|H,I) is typically a gaussian function, referred to as the Likelihood Function. If you pick a poor model for the waveform sought, the probability density which you compute will not be localized. The analysis is telling you that all values of the model parameter are equally good (or poor). If you have a good model, but search for the model parameter outside the correct range, the probability density will again give a poor estimate of model parameters. The hardest part of most engineering problems is identifying the question.

The round-trip delay is the inverse of this period.

5. Conclusion

As we suggested, the costs of a significant experiment have been greatly reduced from the alternative laboratory experiences. This experiment is important, as it illustrates the effects of terminating transmission lines, the standing waves on poorly matched lines, and it also illustrates the synthesis of a radar signal from simple signal sources. Some aspects of this laboratory have been available, but neglected in many courses. The concept of characteristic impedance is of equal importance to the radio engineer using an antenna, the power engineer with transmission lines, or the computer engineer sending signals to a computer. The better software [4, 5] available now makes this classic experiment of greater value to a broader audience.

Acknowledgment

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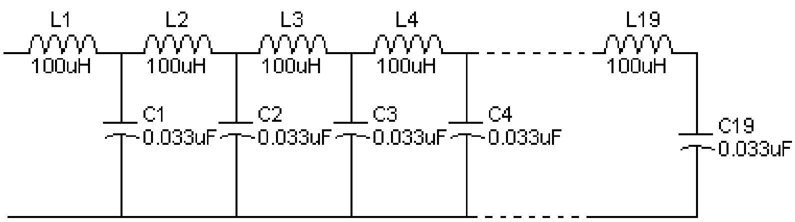

Figure 1. Schematic diagram of prototype board of 19 sections

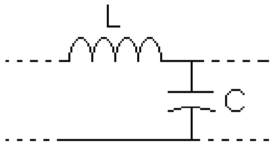

Figure 2. Single section of L-C Ladder

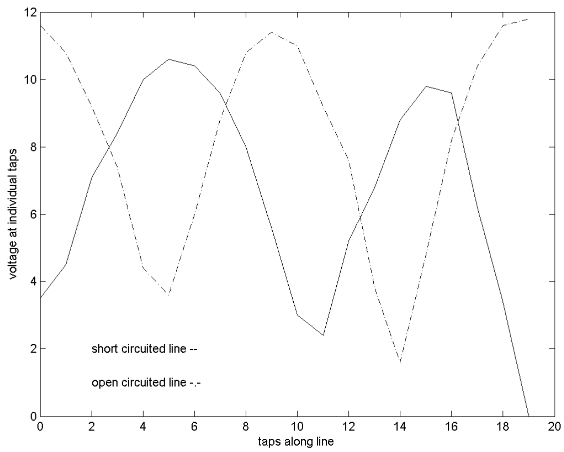

Figure 3. Open and short measurements versus tap position at a frequency of 30 kHz

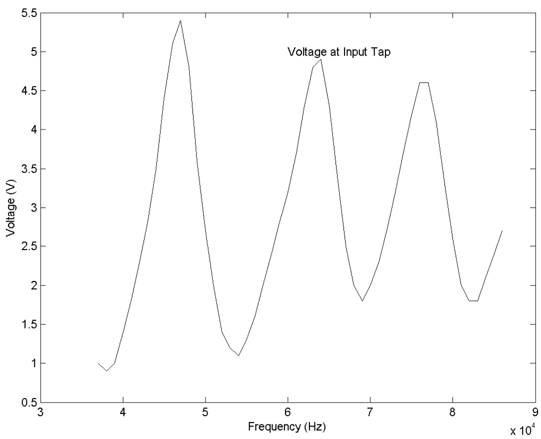

Figure 4. Input voltage versus signal frequency for open circuited line

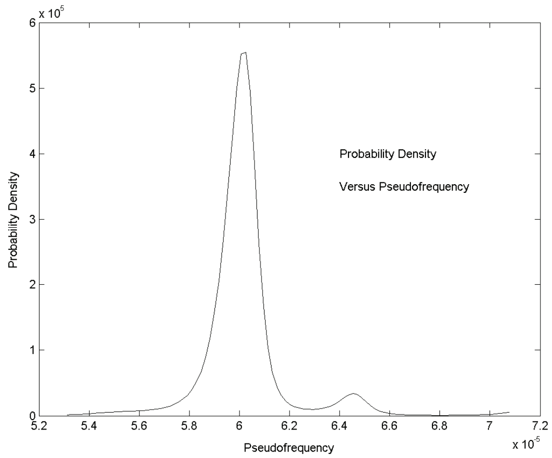

Figure 5. The pseudofrequency spectrum of Figure 4 data.